

The 3.5 keV X-ray line from decaying gravitino dark matter

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Abstract

Extremely weakly interacting particles like the gravitino may be stable enough on cosmological time scales to constitute a good dark matter candidate even in the presence of R-parity violation. We consider the possibility that the recently identified 3.5 keV X-ray line can be generated in light gravitino decays to neutrino and photon. We find that this is indeed possible in loop processes induced by trilinear lepton number violating couplings. We show that in order to avoid over-production of gravitinos, the reheating temperature has to be below about 170 GeV. Finally we briefly discuss associated LHC phenomenology due to a relatively light gluino and multi-jet/multi-lepton events from R-parity violating decays of neutralinos.

1 Introduction

Despite the abundance of gravitational evidence of the existence of dark matter, a confirmed detection signal through non-gravitational modes is still lacking. However, with the improving sensitivity in cosmic ray measurements, direct detection experiments and increasing reach in collider searches, a genuine dark matter signal could be expected.

In fact, recent studies of stacked X-ray spectra from the XMM-Newton telescope, have revealed an unidentified line with the central energy of 3.5 keV [1, 2]. However, one should bear in mind that the significance of the signal is not that high yet ($\simeq 4 - 5 \sigma$ [1]) and that, while more conventional explanations of the line in terms of atomic physics effects are currently lacking, they have not been ruled out. On the other hand, it is tempting to consider more exotic explanations of the signal in terms of decaying or annihilating dark matter since a monochromatic photon line signal would be a smoking gun of dark matter. While annihilating dark matter does not seem compatible with the signal [3], it is possible to explain it with eXciting dark matter [4], where the photons come from the transition from the excited state down to the ground state for the dark matter particle, which in this case can be significantly heavier than 3.5 keV.

Interpretations in terms of light decaying dark matter seem more promising in meeting the conditions implied by the data. The required properties of such dark matter is [1, 2]:

$$\begin{aligned} m_{\text{DM}} &\simeq 7 \text{ keV}, \\ \tau_{\text{DM}} &\simeq 10^{28} \text{ s}. \end{aligned} \tag{1}$$

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In fact, several candidates have already been considered in this context, and sterile neutrinos [5], axions [6] and axinos [7] have already been demonstrated to be able to produce the observed line through their decay. Also decaying moduli [8] and millicharged dark matter [9] as well as multicomponent dark matter [10] have been shown to be compatible with the data.

In this paper, we consider the possibility that the X-ray line is produced by the gravitino decaying through R-parity violating processes to, e.g., a photon and a neutrino. While LHC data imply that the masses of ordinary sparticles are in the TeV range, this does not necessarily apply to the gravitino since its mass is set by the scale of supersymmetry breaking and it does not have to be similar to the other sparticles. As a matter of fact, in gauge mediated supersymmetry breaking a keV-scale gravitino mass is natural [11].

It is also worth mentioning that such a light gravitino would potentially constitute warm dark matter [12] and hence help solve some possible problems of the cold dark matter paradigm, most notably the cusp-core problem and the missing satellite problem, although other solutions are also possible.

The rest of this paper is structured as follows. In Section 2 we discuss the decay channels for a light gravitino in R-parity violating supersymmetric models and calculate the relevant decay widths. In Section 3 we discuss the compatibility of this scenario with early universe cosmology, especially the issue of not over-closing the universe with gravitinos, and we make comments about associated LHC phenomenology. Section 4 contains our conclusions.

2 R-parity violating decay of gravitino dark matter

If the requirement of R-parity conservation is lifted, a number of terms become allowed in the superpotential. These are trilinear and bilinear lepton number violating terms [13]:

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \mu_i H_1 L_i, \quad (2)$$

where $i, j, k = 1, 2, 3$, L_i, Q_i, H_1 are left-chiral lepton, quark and Higgs superfields and E_i, D_i are right-chiral lepton and down quark superfields, as well as trilinear baryon number violating terms

$$\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k, \quad (3)$$

where D_i, U_i are right-chiral down and up quark superfields.

If R-parity is violated, supersymmetry does not provide any stable dark matter candidate. However, the gravitino can, due to the smallness of its interactions, still be long-lived enough to constitute the missing matter of the universe [14, 15, 16].

The question we want to address is whether decaying gravitino dark matter could be the cause of the 3.5 keV X-ray line recently reported. The baryon number violating terms of Eq. (3) do not induce any gravitino decay including a monochromatic photon line, and hence we can ignore them from now on; note also that proton stability requires the absence of combinations of baryon number and lepton violating terms and therefore we shall assume the terms of Eq. (3) to all be zero.

If R-parity is violated by the bilinear terms μ_i , a decay $\tilde{G} \rightarrow \nu\gamma$ is allowed which gives the required signature for the gravitino mass of 7 keV. However, it turns out that the lifetime associated with it is given by [14]

$$\tau_{\tilde{G}} \approx 4 \times 10^{11} \text{ s } |U_{\nu\tilde{\gamma}}|^{-2} \left(\frac{m_{\tilde{G}}}{10 \text{ GeV}} \right)^{-3}, \quad (4)$$

where $U_{\nu\tilde{\gamma}}$ is the mixing between neutrinos and photinos induced by the μ_i couplings and $m_{\tilde{G}}$ is the gravitino mass. For the required gravitino mass of 7 keV, Eq. (4) gives $\tau_{\tilde{G}} \approx 1.1 \times 10^{30} \text{ s } |U_{\nu\tilde{\gamma}}|^{-2}$ which exceeds the values required to explain the observed line. This was also pointed out in [17] where it was concluded that although there are several sparticles capable of explaining the line signal in R-parity violating supersymmetry, the gravitino is not one of them, however, as we will see below, this conclusion changes if we also take trilinear R-parity violation into account.

On the hand, it was demonstrated in [18] that trilinear lepton number violating couplings λ_{ijk} and λ'_{ijk} allow for sfermion-fermion loops that also can produce the required $\tilde{G} \rightarrow \nu\gamma$ decay. In order for the loop decay to be possible one needs two identical flavours in the operator so this can only happen if $i = k$ or $j = k$ for λ_{ijk} couplings, in which case the loop will contain lepton and slepton lines of flavour k , or if $j = k$ for λ'_{ijk} couplings, in which case the loop will consist of down quark and squark propagators of flavour k .

The decay width due to the loop decays is given by [18]:

$$\Gamma_{\tilde{G}} = \frac{\alpha \lambda^2 m_{\tilde{G}} m_f^2}{2048 \pi^4 M_p^2} |\overline{\mathcal{F}}|^2, \quad (5)$$

where $M_p = 2.4 \times 10^{18} \text{ GeV}$ is the reduced Planck mass, m_f is the mass of the fermion in the loop and $|\overline{\mathcal{F}}|^2$ is a loop factor given (with a minor correction as compared to [18]) in Appendix A of [19].

While the tree-level three-body decay through the trilinear terms give a decay width $\propto m_{\tilde{G}}^7$, and hence becomes negligible for small gravitino masses, the loop decay gives a width $\propto m_{\tilde{G}}$ and therefore dominates at small masses [19]. Note that this means the loop decay also decreases much more slowly than the bilinear induced decay when the gravitino mass is decreased, therefore it opens the possibility of explaining the observed excess.

For small gravitino masses the decay width is essentially independent of the other sparticles' masses, the only dependence is on the RPV coupling and the mass of the fermion in the loop. The latter dependence is a consequence of the helicity structure of the diagram that requires a helicity flip whose probability depends on the mass term for the fermion. To calculate the lifetime of the gravitino we use Eq. (5) together with LoopTools [20] for the loop factor $|\overline{\mathcal{F}}|^2$. The result is given in Table 1 where the coupling strength required to obtain a lifetime of 10^{28} s for each of the particles that can appear in the loop, is shown.

Since couplings larger than unity are problematic for perturbativity reasons as well as in conflict with experiment for most couplings, we see in Table 1 that electron or d-quark couplings are too large. However, all the other cases seem compatible with the observed line. As expected the b-quark loop requires the smallest coupling of only 2×10^{-3} . When

Table 1: The coupling strength required to obtain a lifetime of 10^{28} s for the various particles that can appear in the loop. The third column gives the couplings that can give rise to the mentioned loops.

particle in loop	λ required for $\tau_{\tilde{G}} = 10^{28}$ s	Couplings
electron	17	$\lambda_{121}, \lambda_{131}$
muon	0.081	$\lambda_{122}, \lambda_{232}$
tauon	0.0094	$\lambda_{133}, \lambda_{233}$
d-quark	1.4	λ'_{i11}
s-quark	0.048	λ'_{i22}
b-quark	0.0023	λ'_{i33}

comparing the values in Table 1 with experimental constraints [21], we see that at least the muon loop contribution is in conflict with constraints for sparticle masses of 100 GeV, however, in light of the lack of detection at the LHC, such low sparticle masses are not realistic and for sparticle masses above 1 TeV there is no conflict with the above mentioned constraints.

There are also constraints coming from the neutrino masses [22], but they are highly dependent on the full particle mass spectrum so there should always be room to meet those constraints.

From a model building point of view, one often expects the flavour structure of the trilinear R-parity violating couplings to resemble the flavour structure of the standard model Yukawa couplings and hence one would expect that the couplings including heavy flavours (especially λ'_{i33}) are the largest [23]. This is in good agreement with our finding that couplings with heavy flavours are the most suited to explain the 3.5 keV X-ray line discussed here.

3 LHC signatures and relic density of gravitinos

One important issue for gravitino dark matter is the production of the correct relic density. The thermal relic density of gravitinos, $\Omega_{\tilde{G}} h^2$, is given by the gravitino mass, $m_{\tilde{G}}$, the reheating temperature, T_R , and the gluino mass, $m_{\tilde{g}}$, according to [24],

$$\Omega_{\tilde{G}} h^2 = 0.27 \left(\frac{100 \text{ GeV}}{m_{\tilde{G}}} \right) \left(\frac{T_R}{10^{10} \text{ GeV}} \right) \left(\frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2. \quad (6)$$

From Eq. (6) we see that for a gravitino as light as 7 keV, in order to avoid over-production, one would need a light gluino, however, that looks incompatible with LHC constraints.

Without detailed knowledge of mass hierarchies among the sparticles, it is impossible to give an exact number for the limit on the gluino mass. However, as a crude estimate we can

assume that the gluino is the lightest ordinary sparticle and it is being produced in pairs that subsequently decay through a λ'_{i33} coupling to two b-jets and a neutrino. (Here we assume that the decay to a charged lepton, a top quark and a b-quark is essentially absent due to phase-space suppression by the top mass, if this channel is significant, it should if anything strengthen the constraint due to its easier detection.) The resulting topology of four b-jets and missing transverse energy has been searched for in the context of gluinos decaying to b-quark pairs and neutralinos [25, 26]. There are also searches for gluinos decaying to quark pairs and neutralinos [27, 28] and they are slightly more constraining with the best limit (for zero neutralino mass) being $m_{\tilde{g}} \gtrsim 1400$ GeV. In terms of reheating temperature this translates to $T_R \lesssim 170$ GeV.

One should also keep in mind that it is also possible to generate a significant amount of non-thermal gravitino population through decays of heavier sparticles. However, this is only important if the reheating temperature is comparable to or larger than the mass of the sparticles in question [29]. As seen above, we expect a rather low reheating temperature and hence we do not consider non-thermal production in the further discussion.

One should also note that it is possible to have late time entropy creation from the decay of other relics [30] which can wash out the gravitino density and hence alleviate the constraint on T_R stated above.

In this scenario thermal leptogenesis is clearly impossible, firstly because the reheating temperature is too low and while it is possible to achieve high enough reheating temperature by late time entropy production [31], the lepton number violating couplings will erase the lepton asymmetry before the electroweak phase transition [32]. However, the reheating temperature potentially remains above the electroweak phase transition temperature, possibly leaving some room for electroweak baryogenesis to account for the baryon asymmetry of the universe [33].

The violation of R-parity has rather significant implications for LHC phenomenology [34]. Most importantly the neutralino, even if lighter than all other sparticles of relevance to the LHC, is no longer stable and hence will not give rise to missing transverse energy but will rather decay into final states of Standard Model particles. For LHC studies of all possible decay topologies, see [35]. If the gravitino decay is due to a tau loop, the LHC phenomenology of decaying neutralinos is promising, the final state will consist of multiple leptons and missing transverse energy, and although many of the leptons will be taus this would be clearly detectable if the neutralino production (either direct or through decay) is large enough. Even more promising would be the muon case where a large part of the final state leptons would be muons.

For squark loops the expected signature would be multiple jets and some missing transverse energy (from neutrinos) and/or charged leptons, which, although not as clean as the multi lepton case, should be clearly seen. The least promising option, which might also be the most likely, would be a b-quark loop which leads to a final state of b-jets and missing transverse energy. However, as seen above, such final states are also under control by the LHC experiments. Also note that if the neutralino is heavy enough, it can decay to a charged lepton, a top quark and a b-quark, and that should be a rather clean signal even if the branching fraction is small due to phase-space suppression.

4 Conclusions

The possible existence of a X-ray line consistent with decaying dark matter is an intriguing possibility. In this paper we have demonstrated that such a signal can indeed be interpreted in terms of decay products of gravitino dark matter if R-parity is violated by trilinear lepton number violating couplings which induce loop decays of the gravitinos to neutrinos and photons. Couplings as small as 2×10^{-3} are shown to be capable of explaining the observed line, which means all present constraints are satisfied.

The low gravitino mass of 7 keV required to fit the line means that the reheating temperature of the universe cannot be too high; without any late time entropy production, we arrive at an upper bound of $T_R \lesssim 170$ GeV in order to avoid over-closure of the universe by the gravitinos. This leaves no room for thermal leptogenesis to account for the baryon asymmetry of the universe (even if late time entropy production is included to raise the reheating temperature, the R-parity violating couplings will still erase any lepton asymmetry), but electroweak baryogenesis might still be viable.

One would also expect the gluino to not be too heavy and that, together with the multi-lepton or multi-jet final states expected from neutralino (or possibly gluino) decay through the R-parity violating couplings responsible for the gravitino decay, would be very promising for future searches of supersymmetry signal with R-parity breaking at the LHC.

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